



RESEARCH DEPARTMENT



REPORT

Design of a prototype
moving-coil high-frequency
loudspeaker drive unit.

K.E. Randall, M.I.E.E.

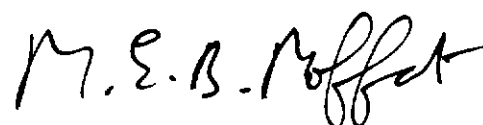
THE DESIGN OF A PROTOTYPE MOVING-COIL HIGH-FREQUENCY
LOUDSPEAKER DRIVE UNIT

K.E. Randall, M.I.E.E.

Summary

A high-frequency loudspeaker drive unit (tweeter) suitable for use in a high-quality studio monitoring loudspeaker is described and the necessary manufacturing information provided. Design considerations are outlined and development problems discussed. Performance is assessed and possible improvements are suggested.

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THE DESIGN OF A PROTOTYPE MOVING-COIL HIGH-FREQUENCY LOUDSPEAKER DRIVE UNIT

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1. Introduction

The tweeters (high-frequency drive units) used in BBC designed monitoring loudspeakers have always been of commercial manufacture and have generally been selected from a production run to meet a specified sensitivity and frequency response. The BBC possesses considerable expertise in the design of bass (low-frequency) drive units but until now has not acquired similar experience in the design of tweeters.

The two most recent studio monitoring loudspeakers, namely the LS5/8 and LS5/9 (1,2) each incorporate two drive units. The bass units of 300 mm and 200 mm respectively are of BBC design and the tweeter in both cases is a commercially-made 34 mm soft-domed moving coil unit. The tweeter, which takes over from the bass unit at approximately 2 kHz, has generally proved to be satisfactory although some batches have varied in performance at the upper end of the frequency range. There is also the possibility that a commercially designed unit may be modified or discontinued, whereas an in-house design could be supplied by more than one manufacturer or even produced in-house if required. These considerations led to the decision to acquire experience in the design and manufacture of tweeters.

This Report describes a number of different types, assesses the performance of a number of commercial units, and gives reasons for choosing the moving-coil type as the one most likely to be suited to BBC requirements.

An in-house design is described together with performance details and it is concluded that it could be considered as a replacement unit for the one presently used in the LS5/8 and LS5/9 monitoring loudspeakers should this become necessary. Possible shortcomings in the design and suggestions for improvements are discussed.

2. Description of tweeter types

2.1. General

Electroacoustic conversion may be achieved by electromagnetic, piezoelectric or electrostatic means

(3). The electromagnetic tweeter is most commonly of the moving-coil type in which a coil in a radial magnetic gap is subjected to an axial force; the acoustic radiator is a dome-shaped diaphragm attached to the coil. A variant of this is the much less common ribbon type which is, in effect, a half-turn moving-coil with the ribbon itself as the acoustic radiator.

The most common form of piezoelectric tweeter comprises a ceramic element driving a horn-loaded diaphragm; recently however direct radiating piezoelectric tweeters have been developed. An electrostatic tweeter comprises a flat radiating element which is acted upon by a uniform electric force over its whole surface.

To enable an assessment of the performance of different types of tweeter to be carried out a representative selection was purchased and measurements of frequency response, sensitivity, distortion and directional response were made, together with an assessment of mechanical and electrical ruggedness and probable ease of manufacture.

2.2. Moving-coil

Fig. 1 shows the construction of the moving-coil tweeter (subsequently referred to as the current unit) used in the LS5/8 and LS5/9 loudspeakers (1,2). The diaphragm, formed from impregnated woven fabric, comprises a radiating dome which is integral with a surrounding roll and clamped around its outer edge. The roll provides both the termination for the diaphragm and the restoring force for the moving system, thereby combining the functions of suspension (spider) and surround found in other types of moving coil drive unit.

Fig. 2 (a) shows the on-axis response/frequency characteristic of the current tweeter together with the 2nd harmonic distortion (the level of 3rd harmonic distortion is below 30 dB SPL). Fig. 2 (b) shows the response/frequency characteristic on-axis together with the response at 30° and 45° off-axis.

2.3. Ribbon

In a ribbon tweeter (4) the impedance match between the ribbon and the air is very poor and

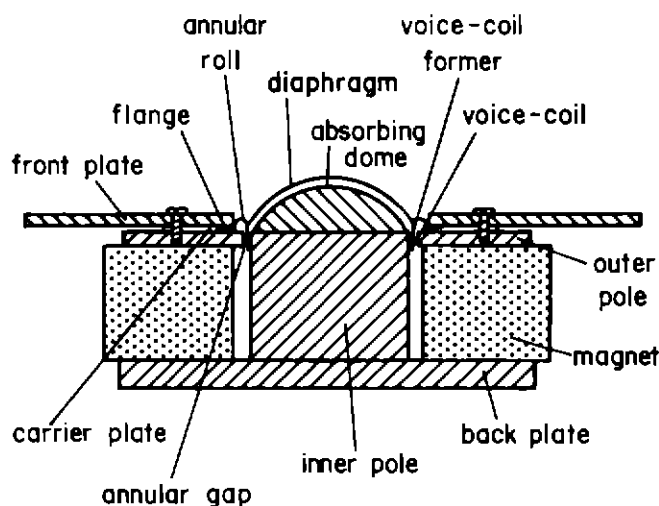


Fig. 1 - The construction of a moving-coil tweeter.

consequently acoustic conversion efficiency is very low. The addition of a horn (Fig. 3) provides a generally improved but highly frequency dependent match between the ribbon and the air. It therefore increases efficiency but at the expense of irregularities in both response/frequency characteristic and directionality.

Fig. 4(a) shows the on-axis response/frequency characteristic of one type of ribbon tweeter together with the 2nd and 3rd harmonic distortion, and Fig. 4(b) shows the response/frequency characteristic on-axis together with the responses at 30° and 45° off-axis.

2.4. Piezoelectric

The horn-loaded piezoelectric tweeter (5), (Fig. 5) is a very efficient radiator but exhibits irregularities in both response/frequency characteristic and directionality. Fig. 6(a) shows a typical on-axis response/frequency characteristic together with the 2nd harmonic distortion, whilst Fig. 6(b) shows the response/frequency characteristic on-axis together with the response at 30° and 45° off-axis.

Direct radiating piezoelectric tweeters using synthetic polymers were the subject of a feasibility study carried out in BBC Research Department in 1981 (6). A recently available commercially manufactured unit with a 60 mm diameter diaphragm (Fig. 7) was included in the current assessments and Fig. 8(a) shows the on-axis response/frequency characteristic together with the 2nd and 3rd harmonic distortion. Fig. 8(b) shows the response/frequency characteristic on-axis together with the response at 30° and 45° off-axis.

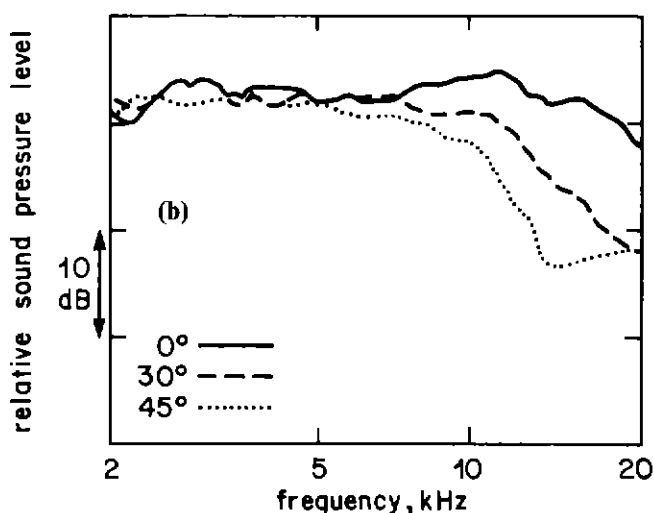
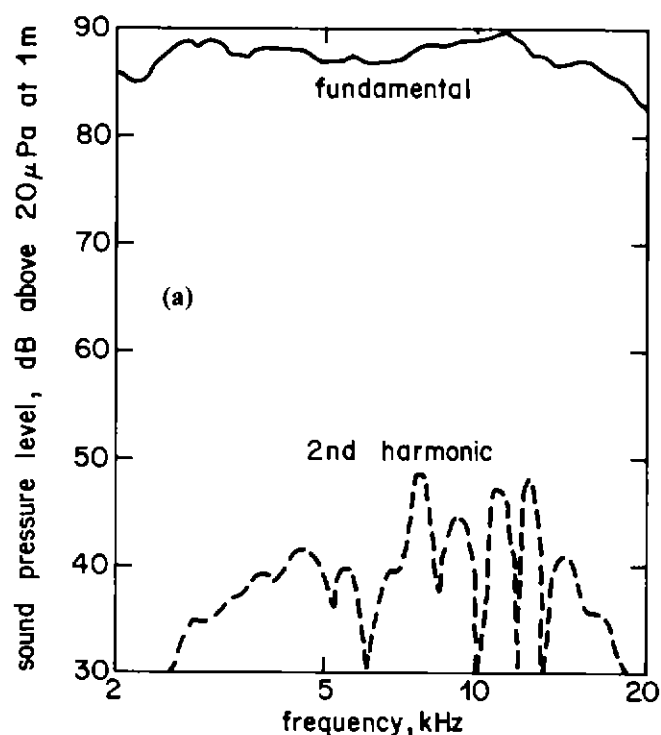


Fig. 2 - Response/frequency characteristics of 34mm moving-coil tweeter. (a) on axis; fundamental and 2nd harmonic, 2V applied. (b) on-axis and two angles off-axis.

2.5. Electrostatic

These devices require an e.h.t. polarizing voltage to be connected across the diaphragm and the electrodes between which it is sandwiched (4); because of this complication it was considered to be unsuitable for BBC use and no assessment of this type was made, although it is acknowledged that excellent sound quality may be obtained.

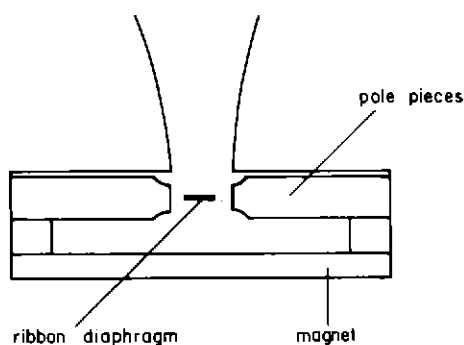


Fig. 3 - Horn-loaded ribbon tweeter arrangement.

3. Design Considerations

3.1. Choice of type

From the assessments carried out on the various types of tweeter it was concluded that the moving-coil type is the one which best fulfils the BBC's requirements of a monitoring loudspeaker for the following reasons:

1. A response/frequency characteristic which is reasonably flat and extends from 2 kHz to 16 kHz.
2. A sound quality free from coloration and subjectively acceptable.
3. An ability to handle input powers necessary for the generation of sound pressure levels in excess of 100 dB at 1 m.
4. A low level of harmonic distortion.
5. Consistency of product.
6. Ruggedness of construction.

The shortcomings of the other types of tweeter when compared with the moving-coil type are uneven response/frequency characteristic and uneven directionality. Further, the ribbon tweeter is fragile and because of the horn is bulky and the response/frequency characteristic of a piezoelectric tweeter does not extend down to a sufficiently low frequency for it to be suitable for inclusion in a two unit loudspeaker design.

3.2. Design criteria

The design criteria chosen for the BBC tweeter are related to the performance of the current unit used in the LS5/8 and LS5/9 loudspeaker designs. Direct replacement is a desirable feature requiring similar overall dimensions, identical fixing arrangements and a matching sensitivity.

The requirement of the design is for a response/frequency characteristic which is smoother and extends to a higher frequency than that of the current unit; reference to Fig. 2(a) shows that the response of the current unit falls rapidly after the

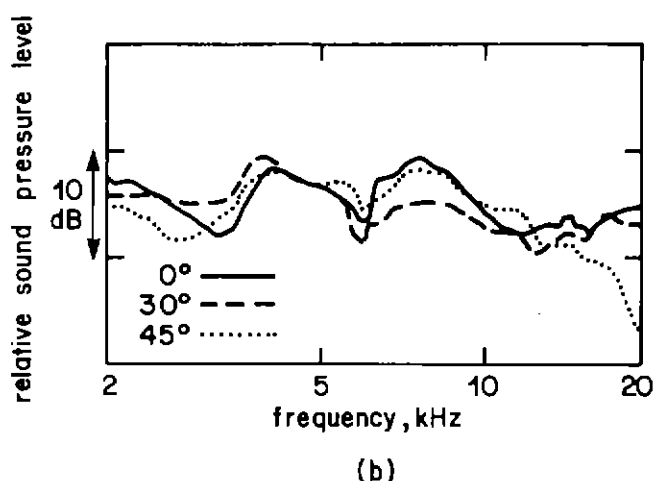
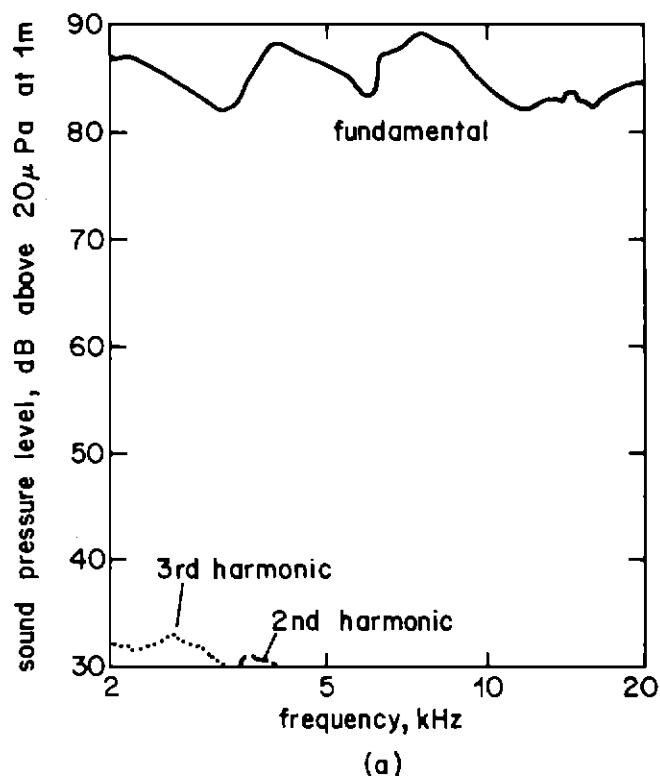


Fig. 4 - Response/frequency characteristics of ribbon tweeter. (a) on-axis; fundamental and 2nd and 3rd harmonics, 2V applied. (b) on axis, and two angles off-axis.

peak at 12 kHz. In addition, the subjective sound quality of the BBC design should match that of the current unit and no colorations should be audible.

3.3. Choice of materials

Since the LS5/8 is able to generate sound levels of 114 dB (LIN) on programme then the tweeter itself may be required to generate sound levels in excess of 100 dB. The large electrical signals necessary to produce these high sound levels will dissipate considerable power in the resistance of the voice-coil and consequently both the voice-coil and its former

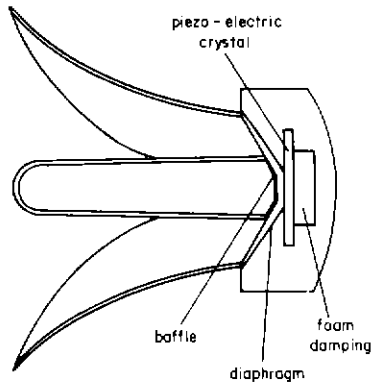


Fig. 5 – The construction of a horn-loaded piezo-electric tweeter.

must be able to withstand the high temperatures generated. Previous experience with the LS5/8 and LS5/9 bass units led to the choice of polyimide-coated wire and sheet polyimide for the voice-coil and former respectively. The proximity of the diaphragm and the voice-coil also means that the diaphragm and adhesives may be subjected to high temperatures, and this must be taken into account in the choice of materials.

The sensitivity of a tweeter is inversely proportional to the moving mass and therefore it is preferable that the diaphragm should be made of a low density material which should also be mechanically lossy, since this latter property will contribute to the smoothness of the response/frequency characteristic and is more likely to produce a sound which will be free from colorations. If the material chosen, because of other considerations such as low density or ease of fabrication, has a low inherent lossiness, then it may be necessary to apply a damping layer to the diaphragm, but this will be at the expense of an increase in mass and consequent decrease in sensitivity.

Dome diaphragms are manufactured by a number of loudspeaker component suppliers and most commonly the materials used are synthetic polymers, which may be either film (sheet) or woven filament (fabric). Diaphragms made with fabric must have the spaces between the filaments sealed; the sealant performs the function of making the diaphragm airtight and should also provide mechanical damping.

3.4. Size

The choice of diameter for the dome/voice-coil is dependent upon the acoustic power output required and the allowable directivity of the tweeter.

If one assumes piston-like behaviour for the

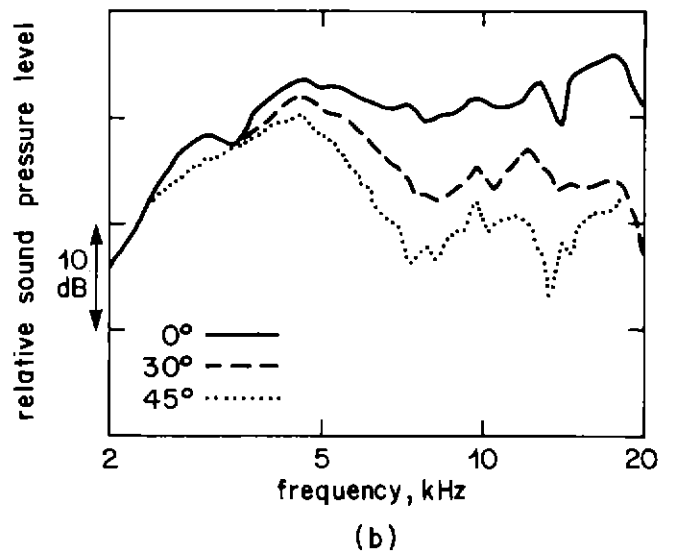
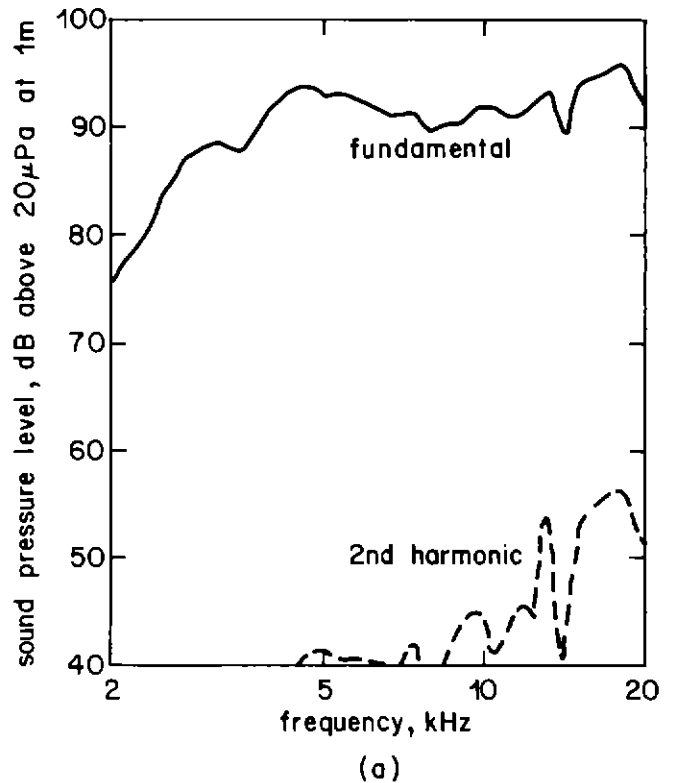


Fig. 6 – Response/frequency characteristics of horn-loaded piezoelectric tweeter. (a) on-axis; fundamental and 2nd harmonic, 2V applied. (b) on-axis and two angles off-axis.

diaphragm then the following relationships are valid:–

$$W \propto u^2 \quad \text{where } W = \text{acoustic output power from diaphragm}$$

$$u \propto r^2 \quad \begin{array}{l} u = \text{volume velocity} \\ r = \text{radius of diaphragm} \end{array}$$

$$\text{therefore } W \propto r^4$$

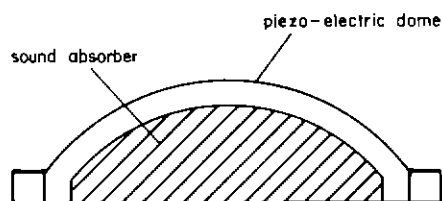


Fig. 7 – The construction of a direct-radiating piezo-electric tweeter.

Since the directivity of a piston in a large baffle increases as the size of the diaphragm increases, a compromise between power output and directivity is necessary. The polar responses of the LS5/8 and LS5/9 loudspeakers are considered to be satisfactory, suggesting that the directivity of the present tweeter is acceptable and, since the output power obtainable is adequate to meet current and foreseeable needs, it was proposed that the size of the diaphragm of the prototype unit should be as near as practicable to 34 mm. Commercially manufactured diaphragms of this size are not generally available, the nearest being 38 mm, and a selection made from different materials and of various shapes was obtained for appraisal. It was intended, however, that the diameter of an in-house manufactured diaphragm would be 34 mm.

4. Description and performance of prototype tweeter

4.1. Introduction

Samples of four different commercial diaphragms were selected, two of woven fabric and two of film, and four prototype designs incorporating these were devised. It was proposed to fabricate at least one example of each and to develop the design which showed most potential to the stage where it would be suitable for use in a monitoring loudspeaker.

4.2. Preliminary designs

The current unit has a doped fabric diaphragm and the response/frequency characteristic of such units is highly dependent upon the mechanical damping properties of the doping compound and the quantity used. For the two tweeters with woven fabric diaphragms it was necessary to develop a suitable dope, since formulations of dope used to treat commercially manufactured tweeters are regarded as confidential.

A number of different formulations were tried, but none was considered satisfactory. The best response/frequency characteristics obtained were not acceptable. Fig. 9(a) shows a typical example.

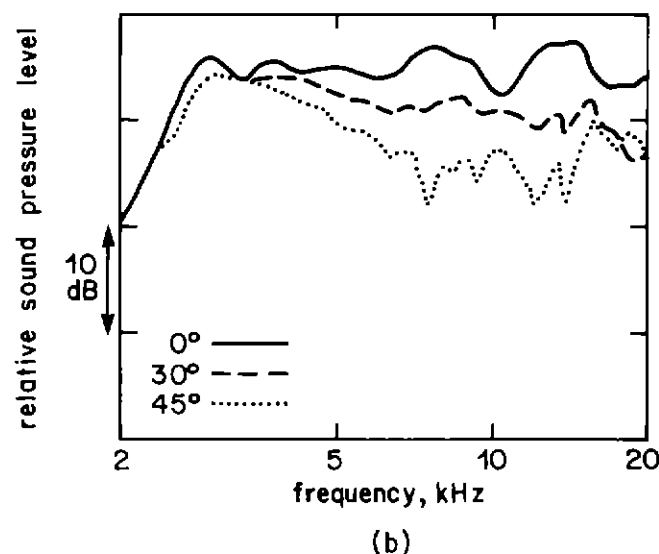
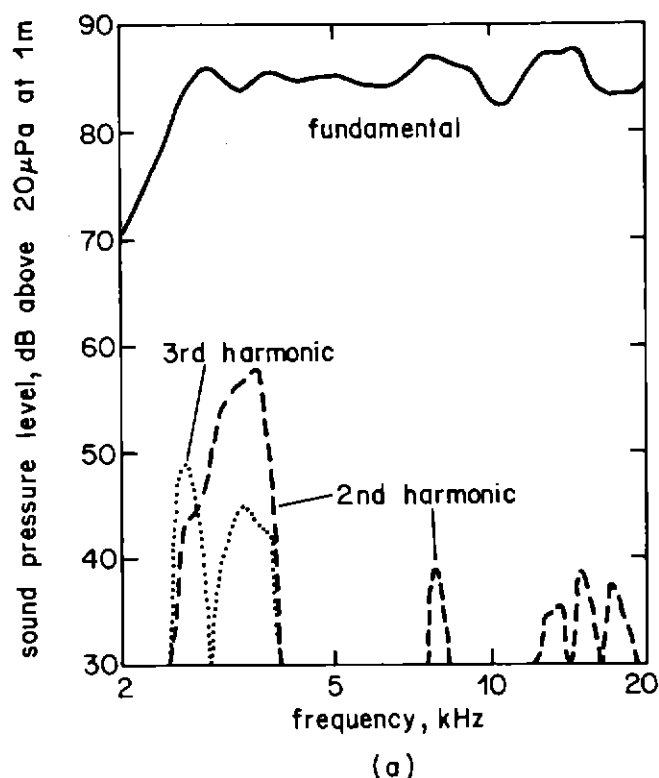


Fig. 8 – Response/frequency characteristics of 60mm direct-radiating piezoelectric tweeter. (a) on-axis; fundamental and 2nd and 3rd harmonics, 2V applied. (b) on-axis and two angles off-axis

Work on the fabric diaphragm units was discontinued because work on film diaphragms, proceeding at the same time offered a better chance of success. Subsequently a doping compound based on bitumen, derived from a self adhesive damping sheet, showed promise and may be useful for any future work.

The two commercially manufactured diaphragm samples made from film were dissimilar, particularly as regards flexibility. The first, coded,

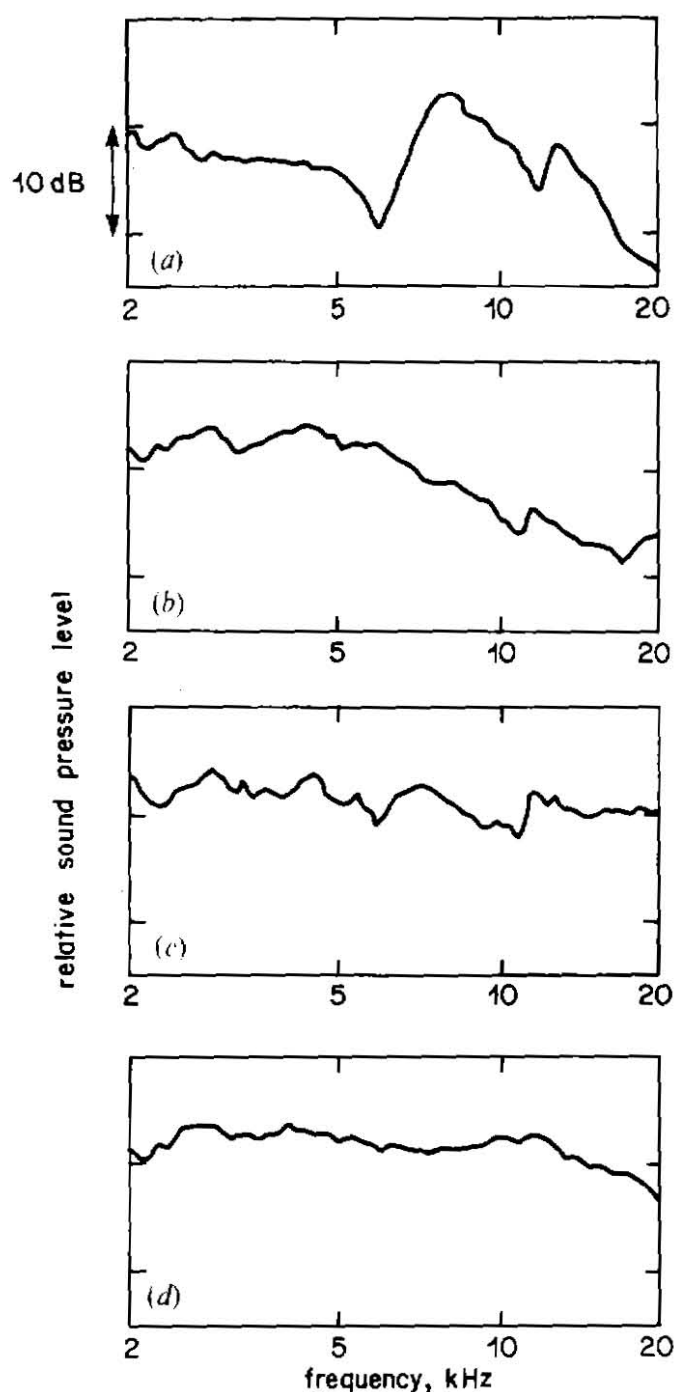


Fig. 9 - Response/frequency characteristics of four designs of tweeter with different diaphragm materials. (a) 38mm doped fabric. (b) 38mm 'SPS' film. (c) 38mm polyester film. (d) 34mm PVC film (vacuum formed in-house).

SPS, was 150 μm thick and very flexible; the second, a polyester, was 75 μm thick and considerably less flexible. Prototype units incorporating the two types of diaphragm were fabricated and the response/frequency characteristics of these are shown in Figs. 9(b) and 9(c). As will be seen the response of the SPS unit falls rapidly above 5 kHz,

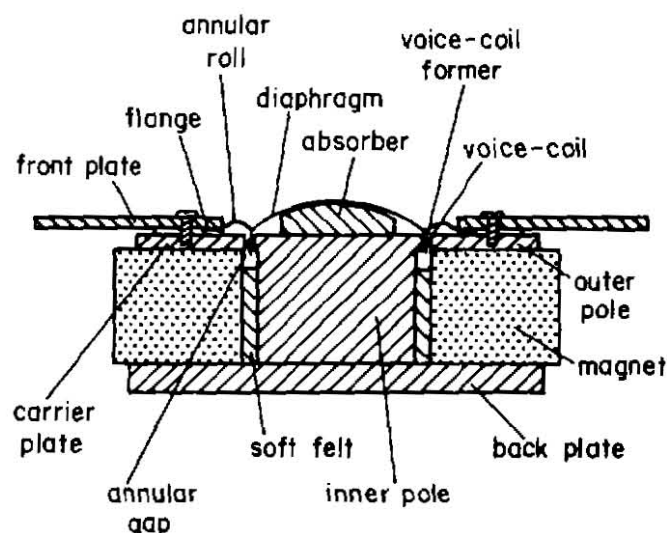


Fig. 10 - The construction of a BBC Prototype 38 mm tweeter.

whereas the response of the polyester unit extends to 20 kHz. In view of the restricted response of the SPS unit no subjective assessments were made on it: however those carried out on the polyester unit suggested that further development was worth pursuing.

To complement the work on commercial 38 mm diaphragms a parallel investigation was carried out using in-house vacuum formed 34 mm diaphragms of 150 μm thick plasticized PVC sheet. A typical response/frequency characteristic is shown in Fig. 9(d), and is seen to be reasonably smooth and to extend to 12 kHz. However, subjective evaluation was rather discouraging because the sound had a prominent coloration in the region of 5 kHz.

For several reasons this work was discontinued. Doubts were expressed about the suitability of using heavily plasticized PVC in regard to its long term physical properties, its mechanical stability and its thermal characteristics. Also despite attempts to improve the vacuum forming technique, there were wide variations in the material thickness in different areas of the diaphragm.

4.3. Final design

Work on the preliminary designs outlined above led to the conclusion that the best chance of success lay in the adoption of a design based on a doped polyester film diaphragm. Fig. 10 shows the construction of the prototype unit which is seen to be essentially the same as the current unit described in Section 2.2.

Important differences are the size and shape of

the diaphragm and the materials from which the diaphragm, voice-coil and voice-coil former are made. The mild steel pole-pieces together with the unmagnetised magnet are glued together with acrylic adhesive; accuracy of fabrication is aided by the use of in-house manufactured jigs. When magnetised, the flux density in the annular gap is 1.5 Tesla.

The voice-coil, once wound, is bonded to the voice-coil former with a high-temperature epoxy resin. The voice-coil, diaphragm and carrier plate are then glued together with cyano-acrylate adhesive. Register pins in the assembly jigs and corresponding ones on the outer pole faces mate with holes in the carrier plate to ensure a high degree of positional accuracy of the voice-coil in the magnetic gap. Fig. 11 shows a completed prototype unit and its sub-assemblies.

4.4. Response/frequency characteristic

The diaphragm is made of polyester film which is a highly undamped (mechanically) material and, as expected, requires the addition of a damping compound to make it suitable. Fig. 12(a) shows the on-axis response/frequency characteristic of the fundamental, 2nd harmonic and 3rd harmonic with a totally undamped diaphragm. Fig. 12(b) shows the result of adding a layer of damping compound to the roll and dome area adjacent to the voice-coil. It can be seen that the curve of the fundamental is considerably smoother, particularly above 5 KHz, together with a considerable reduction in the level of harmonic distortion.

The characteristic shown in Fig. 12(b) includes the effect of damping the magnet and dome cavities.

In contrast Fig. 12(c) illustrates that the effect of removing this damping is to introduce irregularities at 1.5 kHz and 14 kHz. The removal of damping from the magnet cavity, in the form of soft felt wrapped round the lower end of the inner pole-piece, results in the irregularity in the region of 1.5 kHz, which is near to the fundamental resonance of the tweeter. The disc of soft acoustic absorber stuck to the front face of the inner pole-piece, constitutes damping of the dome cavity and is seen to inhibit a peak in the response at 14 kHz.

Comparison of Fig. 12(b) with Fig. 2(a) shows that the on-axis response/frequency characteristic of the prototype falls with increase in frequency, whereas that of the current unit rises. Since the prototype is 2–3 dB more sensitive (note the absolute levels in the region 2 to 5 kHz) it is possible to use equalization to match the prototype to the current unit. Fig. 13(a) shows the response of the prototype and Figs. 13(c) and 13(d) show the response of two examples of current units. The application of simple CR equalization modifies the response of the prototype so that, as is seen in Fig. 13(b), a reasonable match between the current and prototype unit has been achieved. The choice of a more suitable diaphragm material would eliminate the need for the addition of a damping compound and an improvement in the response/frequency characteristic would make it unnecessary to apply equalisation.

4.5. Harmonic distortion

The on-axis response/frequency characteristics of the fundamental and 2nd harmonic are shown in Figs. 14(a) and (b) for the prototype and current units respectively. The 2nd harmonic distortion is

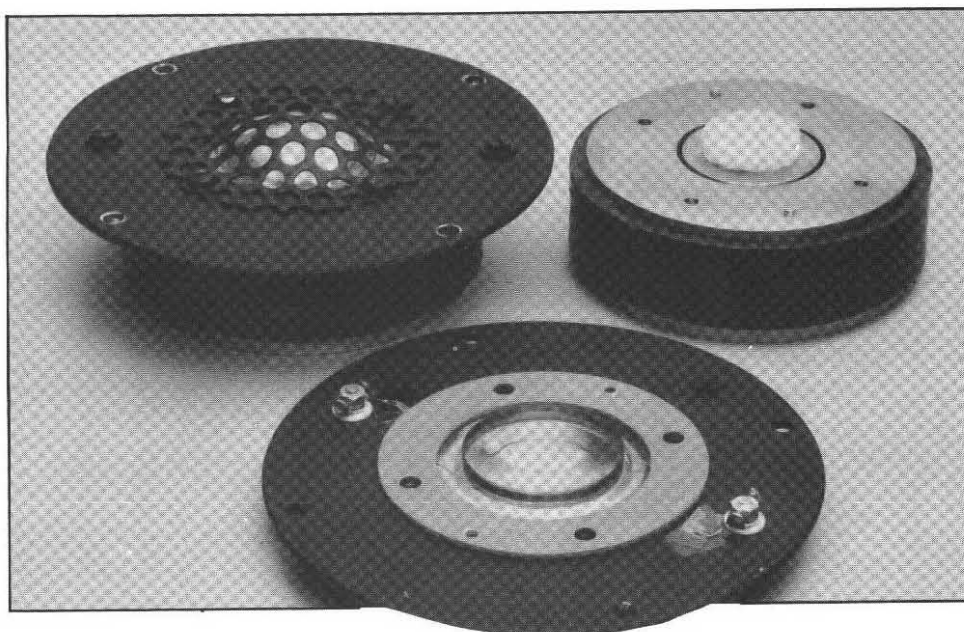
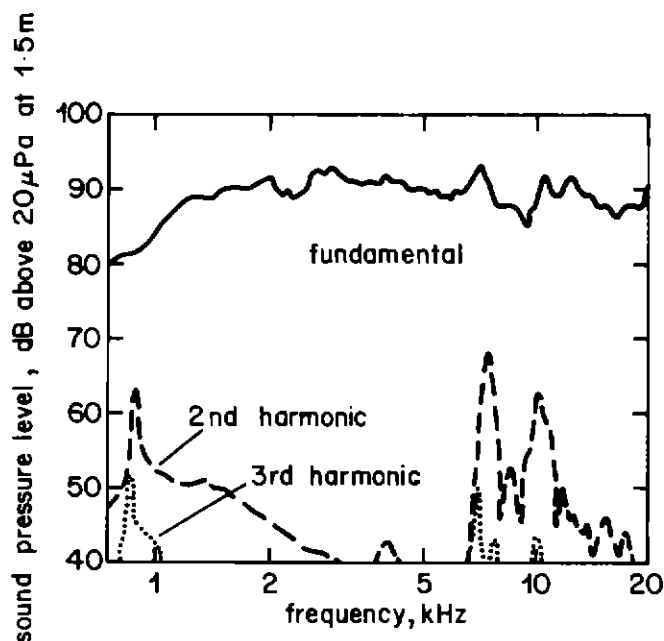
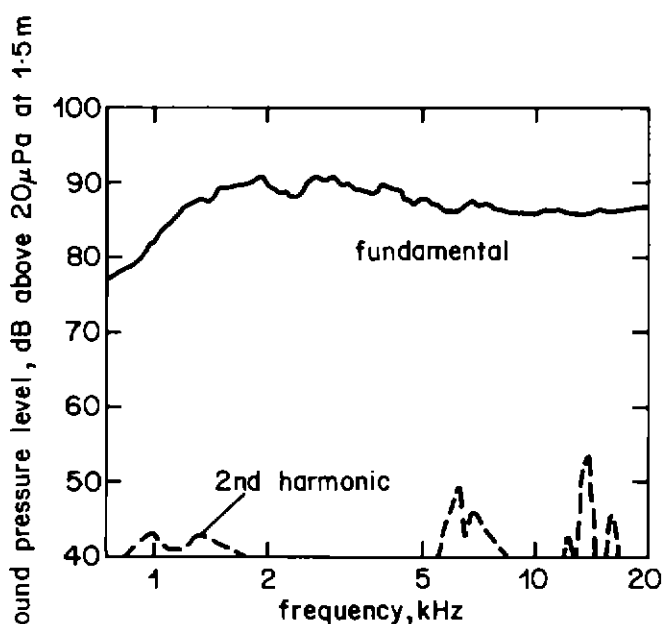


Fig. 11 – Prototype tweeter and subassemblies.



(a)



(b)

below -40 dB for both units with the exception for the prototype which has a -30 dB peak at 14 kHz which is not audible. The 3rd harmonic distortion is below -50 dB for both units.

4.6. Power handling and maximum output level

A number of tests were conducted to assess the power handling capability and maximum sound pressure level obtainable.

To test for electrical and mechanical ruggedness, an equalised prototype unit was fed from a BBC type AM8/16 amplifier which is designed for

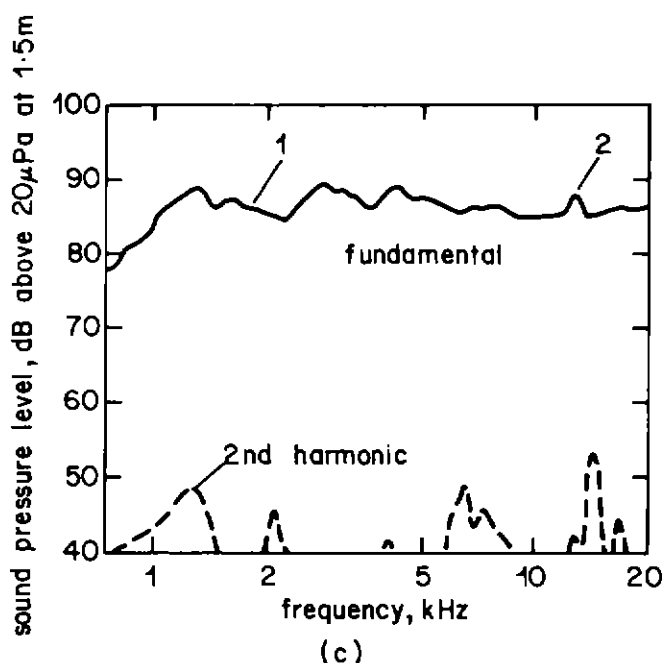


Fig. 12 - On-axis response/frequency characteristics of prototype 38mm tweeter. (a) diaphragm undamped. (b) diaphragm damped. (c) effect of removing damping from (1) magnet cavity (2) dome cavity.

use with the LS5/8 loudspeaker. The AM8/16 is a two channel amplifier which feeds the bass and high frequency units separately and incorporates a low-level crossover network. The power output from the high frequency channel is normally restricted to 18 watts, but for the purposes of this test was allowed to deliver its designed power of 100 W. The amplifier was fed continuously with Radio 2 (light popular music with continuity speech) and was adjusted to give maximum output on programme peaks which produced a sound pressure level from the tweeter of 108 dB at a distance of 1 metre.

The unit operated satisfactorily for 7 days, after which it failed as a result of a pin-point burn-out of the voice-coil. No signs of general overheating, mechanical fatigue or adhesive failure were observed and the temperature of the backplate did not rise above ambient (24°C). A similar test was carried out on a current 34 mm unit. This failed after $4\frac{1}{2}$ days as a result of the voice-coil winding becoming detached from the voice-coil due to failure of the adhesive. Again, no signs of general overheating were observed.

Other (non-destructive) tests carried out were as follows:

- (1) Continuous application of 5 kHz sine waves at 10V rms for a duration of 4 hrs; this produced a sound pressure level of 100 dB at 1 m. The backplate temperature reached stability at 38°C (ambient 24°C).

(2) Continuous application of pink noise (band limited by LS5/8 cross-over network) for a duration of 8 hrs; this produced a sound pressure level of 100 dB at 1 m. The backplate temperature reached stability at 36°C (ambient 24°C).

(3) To assess the maximum undistorted output level obtainable, pulsed sine waves were fed to the unit. The output of a microphone placed 1 m distant from the unit was monitored to detect the onset of distortion. This test was carried out at both 5 kHz and 10 kHz and produced a sound pressure level of 106 dB before the rapid onset of audible distortion occurred.

4.7. Off-axis performance

The response/frequency characteristics of the prototype and current units were measured on-axis and at 15° and 30° off-axis. Each unit was mounted on a 1 m square plywood baffle with the measuring microphone placed at a distance of 1.5 m. The directional response of the units are compared in Figs. 15 (a) and (b) from which it is seen that the off-axis response of the current 34 mm unit is superior to that of the prototype unit. This is to be expected because the diameter of the current unit is less than that of the prototype.

There are at present no agreed performance standards with regard to the directional response of BBC loudspeakers and therefore it is not possible to say to what extent, if any, the more directional performance of the prototype unit will be a disadvantage. In the past certain loudspeakers which were more directional than others were considered to be superior, particularly in respect of stereophonic imaging in the often far from ideal acoustic conditions of many control cubicles.

4.8. Subjective quality

Assessments of subjective quality were made at intervals throughout the development period by means of listening tests carried out by BBC Research Department and Radio Broadcasting staff. Comparisons were made between BBC prototypes and current 34 mm units using a specially modified LS5/8 loudspeaker in which the normal baffle was replaced by one which had provision for mounting two tweeter units side by side (Fig. 16). Facilities for switching between the tweeters were provided, together with independent adjustment of tweeter level to compensate for sensitivity differences between units.

Tape recorded extracts of monophonic speech and music, familiar to the listeners making the comparisons, were played through the loudspeaker.

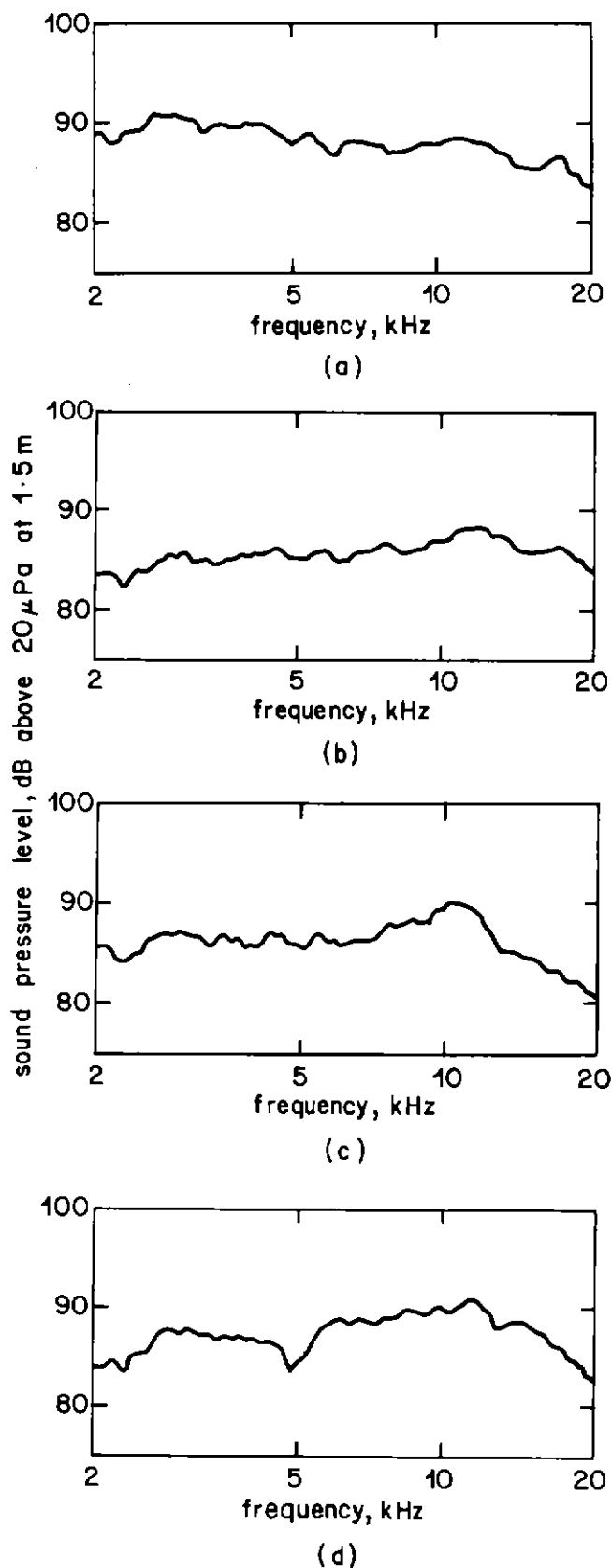


Fig. 13 - On-axis response/frequency characteristics of prototype 38mm unit and two examples of commercial 34mm units. (a) prototype 38mm unit (unequalised). (b) prototype 38mm unit (equalised). (c) typical 34mm unit. (d) typical 34mm unit.

The listeners, who had control of the tweeter switching, made assessments of the quality of the prototype relative to that of the current 34 mm unit which, for this test, was treated as an ideal tweeter. The sound quality of the final version of the prototype unit was judged to be sufficiently close to that of the current 34 mm unit for it to be considered as a replacement in the LS5/8 and LS5/9.

4.9. Consistency of performance

In order to assess the consistency of performance of individual units of the final design, six were made on a "production line" basis. The units were tested both objectively and subjectively, and the range of differences between the six units was no greater than would be expected from six of the current 34 mm units selected from a single production batch.

4.10 Field trials

Preliminary field trials of two of the prototype tweeters have been carried out in the BBC's Quality Monitoring room in London by Radio Broadcasting staff using the two LS5/8 loudspeakers used normally for quality assessment of broadcast output. For these trials the output of the four Radio Networks and Radio London were available in addition to the tape recorded extracts of programme frequently used for loudspeaker quality assessment.

The first listening sessions, which were monophonic only, were a re-appraisal of the performance of the prototype units; for this, the current 34 mm unit in one of the pair of LS5/8s was replaced by a prototype unit and compared with the unmodified LS5/8. The stereophonic performance of the prototype units was also assessed on the pair of LS5/8s, firstly with both loudspeakers modified with prototype units, and secondly with one of the pair modified and the other unmodified. The assessments were carried out over a period of several days during which time the normal activities of quality monitoring were carried out, which therefore included listening to a wide variety of items of broadcast output.

The tests confirmed that the quality of the prototype unit was such that it could be considered as a replacement for the current 34 mm unit for both monophonic and stereophonic listening. The sound quality of the two types was very similar, but certainly not identical, and there was sufficient difference between them for it to be unacceptable to use a mixture of types in a pair of LS5/8 loudspeakers being used for stereophonic listening. The difference in off-axis performance between the tweeter types probably contributed to the un-

acceptability of mixing modified and unmodified loudspeakers for stereophonic listening.

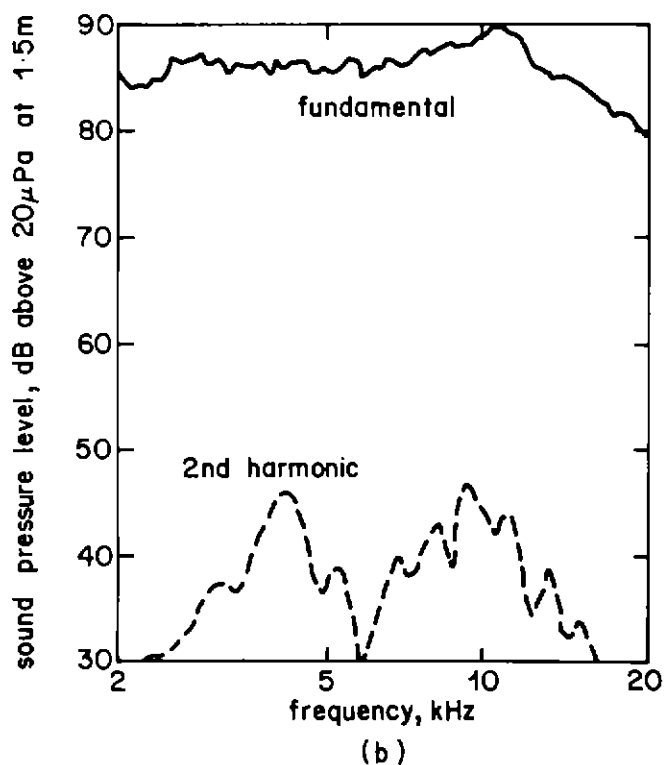
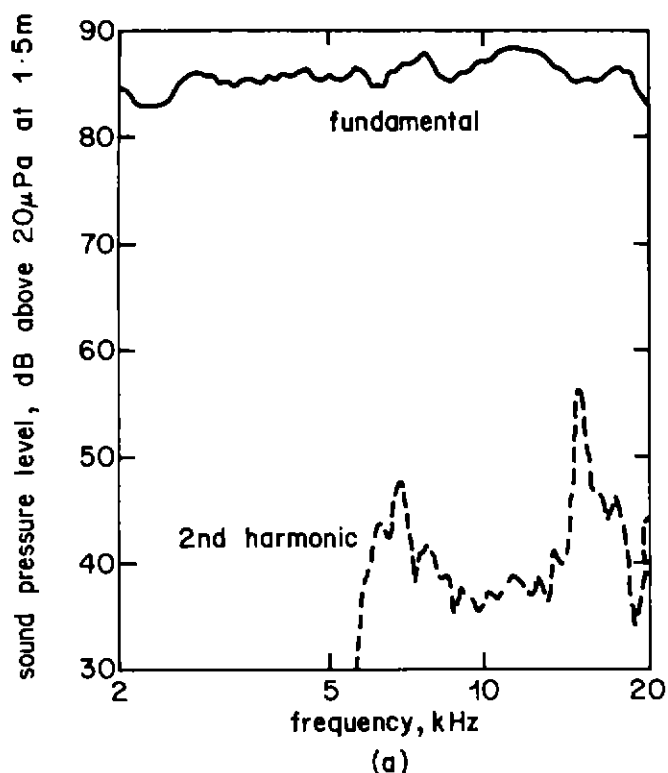


Fig. 14 - 2nd harmonic distortion of prototype 38mm unit and typical commercial 34mm unit relative to fundamental. (a) prototype 38mm unit. (b) typical 34mm unit.

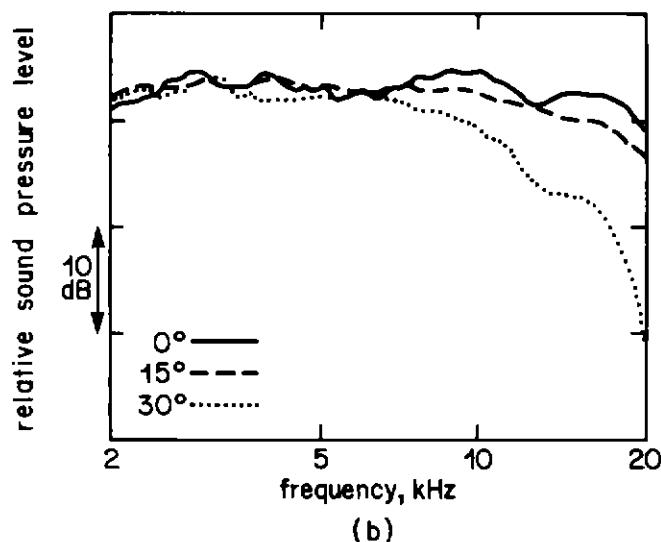
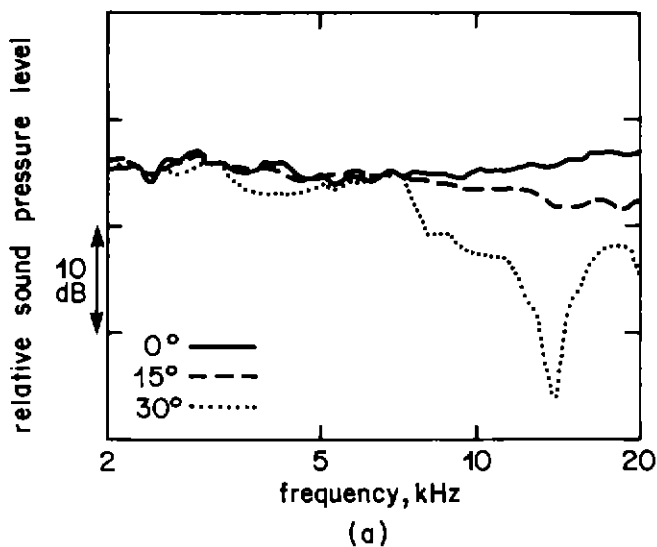


Fig. 15 – Directional response of prototype 38mm unit and commercial 34mm unit. (a) prototype 38mm unit. (b) typical 34mm unit.

5. Conclusions

The design of a prototype moving-coil high frequency loudspeaker drive unit (tweeter) has been described together with some of the problems associated with its development.

A comparison of the objective performance of the BBC prototype with that of the commercial 34 mm unit, which is currently used in the LS5/8 and LS5/9 high-quality monitoring loudspeakers, shows that in respect of harmonic distortion and power handling capability the two types are not very different. Over the range 2 to 10 kHz the response/frequency characteristics of the two types are similar; above 10 kHz the response of the prototype unit is flatter and extends further in frequency. The prototype unit because of its larger diameter has a more directional response than the current 34 mm

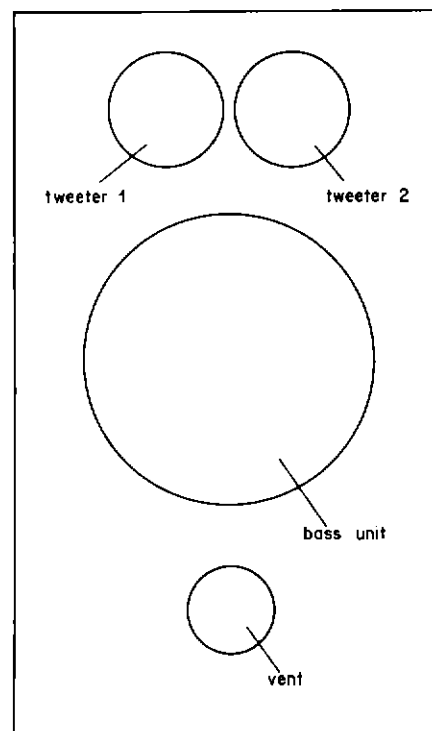


Fig. 16 – Modified LS5/8 baffle for subjective quality comparisons of tweeter units.

unit. Measurements of the objective performance made on six samples of the prototype unit showed a satisfactory standard of consistency.

Comparisons, made during the preliminary field trials, of the subjective performance of the BBC prototype and the current 34 mm units showed, on a wide variety of programme material, that the sound quality was sufficiently similar for the prototype to be a suitable replacement for the current 34 mm unit as used in the LS5/8 and LS5/9 monitoring loudspeakers. There is however sufficient difference between the performance of the prototype and current tweeters for it to be unacceptable to use a mixture of types for stereophonic listening. One of the factors responsible is probably the difference in off-axis performance, although this difference seems to be generally unimportant for the other subjective assessments so far carried out. As a result of this work, the BBC now has some experience in the field of tweeter design and construction which, in the future, may enable it to exert some influence on the design of commercial tweeters.

It is not envisaged that the prototype design will be used operationally in the near future since the current 34 mm unit fulfils present BBC requirements adequately. Any further work should concentrate on improving diaphragm design and finding more suitable materials. Such an investigation would also require improved vacuum forming techniques.

6. References

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